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Investigation of Artificial and Natural Relativistic Electron Loss Processes in the Radiation Belts using the updated SALAMMBÔ Code

Sébastien Bourdarie

CERT/ONERA, Départment de Technologie Spatiale

TOULOUSE, FRANCE

R.H.W. Friedel

LOS ALAMOS NATIONAL LABORATORY, LOS ALAMOS

NEW MEXICO, USA

Contents

A. Abstract

The SALAMMBÔ code is a comprehensive radiation belt transport code. For electrons this code includes pitch angle diffusion due to wave-particle interactions. This part of the code has recently been updated to implement the results of *Abel and Thorne* [1998]. Further the code now models losses due to Synchrotron emission.

We use this new code here to investigate the efficacy of various pitch angle diffusion processes on lowering the relativistic electron fluxes in the radiation belts, both by enhanced natural processes and artificially introduced (man-made) processes. Initial studies have shown that the introduction of additional loss processes for 100 – 500 keV electrons near geostationary altitudes can lower relativistic electron fluxes (~ 2 MeV) in the center of the outer radiation belts ($\sim L = 4.3$) by as much as 30%. We will test these results in the context of the new model.

The long-term goal of this study is to find the optimum combination of natural and artificial loss processes which are needed to significantly reduce the relativistic electron fluxes throughout the radiation belts in a sustainable manner, and to suggest realistic ways of achieving this.

B. Rationale

The energetic radiation belts are the one region in the near-earth Magnetosphere that is reasonably well understood and well modeled. They are also the region of geospace which is most densely populated by satellites, which by nature of the increasing sophistication are becoming MORE susceptible to the natural radiation environment and its dynamic behavior.

Satellites and their electronic components will fail after the total radiation dose has reached the critical limit for the weakest component on board. This is not primarily due to short-term intense events such as magnetospheric storms, but rather due to the long-term accumulation of total dose.

Any technique that can substantially reduce this hazard and increase the reliability and lifetime of such satellites would result in substantial savings. We now have both the theoretical understanding and the practical means to devise systems which can ACTIVELY control the radiation levels in the radiation belts.

As a first step we investigate in this paper where and to what level enhanced diffusion processes have to be induced in the inner magnetosphere to have a long-term affect of reducing the fluxes of "killer electrons" (relativistic electrons greater than 500 keV).

C.1 The Salammbô Code: Description

The Salammbô code is a comprehensive modeling effort for the radiation belts, based on classical diffusive theory [*Schulz and Lanzerotti*, 1974; *Schulz*, 1991]. This code attempts a realistic modeling of the long-term behavior of the radiation belts by including the deceleration of particles by free and bounded thermospheric and ionospheric particles, pitch angle diffusion by wave-particle interactions [*Lyons et al.*, 1972; *Abel and Thorne*, 1998] and Coulomb interactions, the losses due to Synchrotron emissions and radial diffusion by magnetic and electric field perturbations.

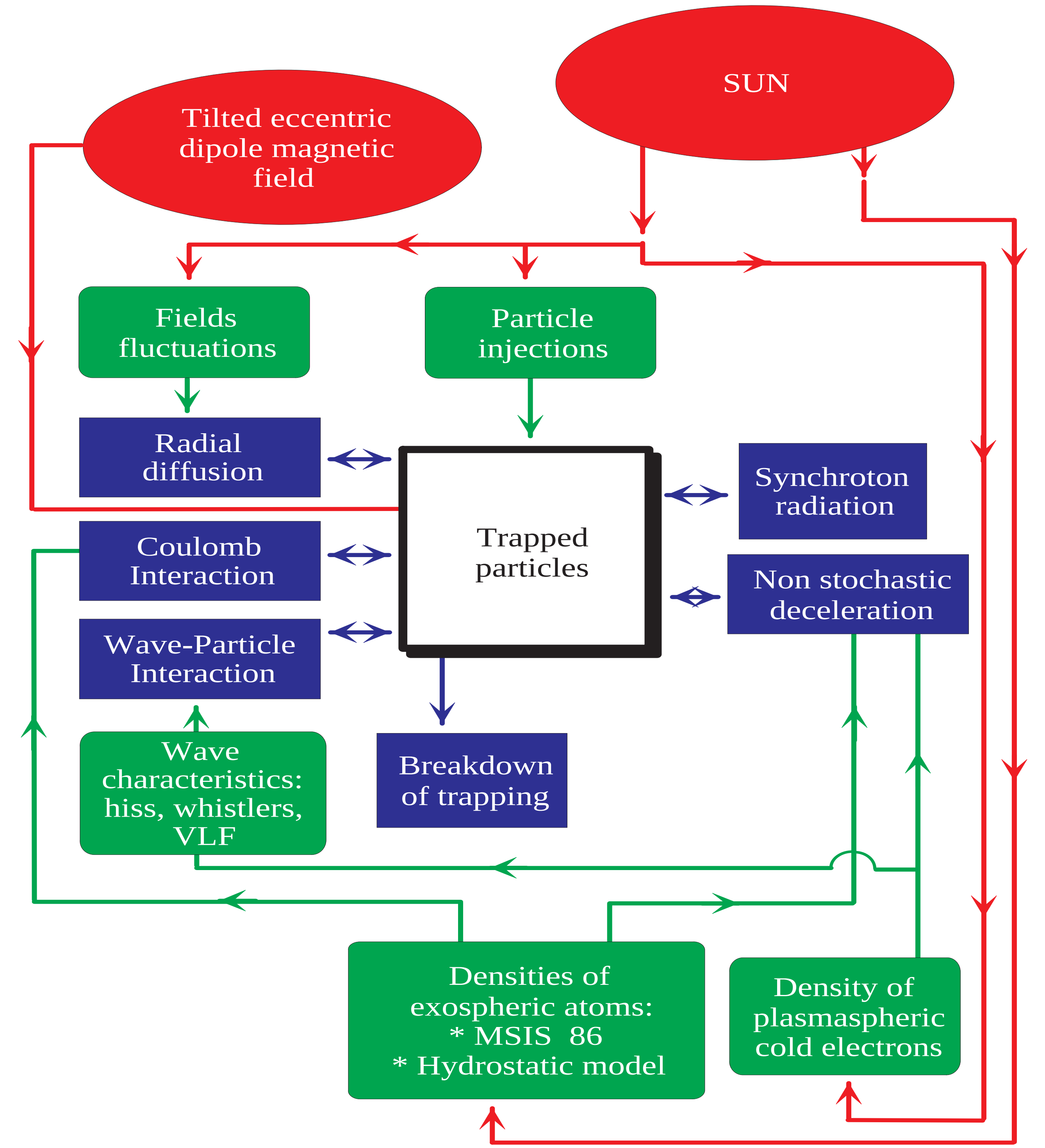
The code is in 3-D in phase space (magnetic moment, 2nd invariant, L), but symmetrical in MLT

Details of the electron and proton model can be found in *Beutier and Boscher* [1995]; *Beutier et al.* [1995].

Applications of the code to modeling the long-term dynamics of the radiation belt protons and electrons has been published[*Boscher et al.*, 1998, submitted] while an extension of the model to four dimensions (mag moment, 2nd invariant, L, MLT) has been used to model the detailed dynamics during storms [*Bourdarie et al.*, 1997].

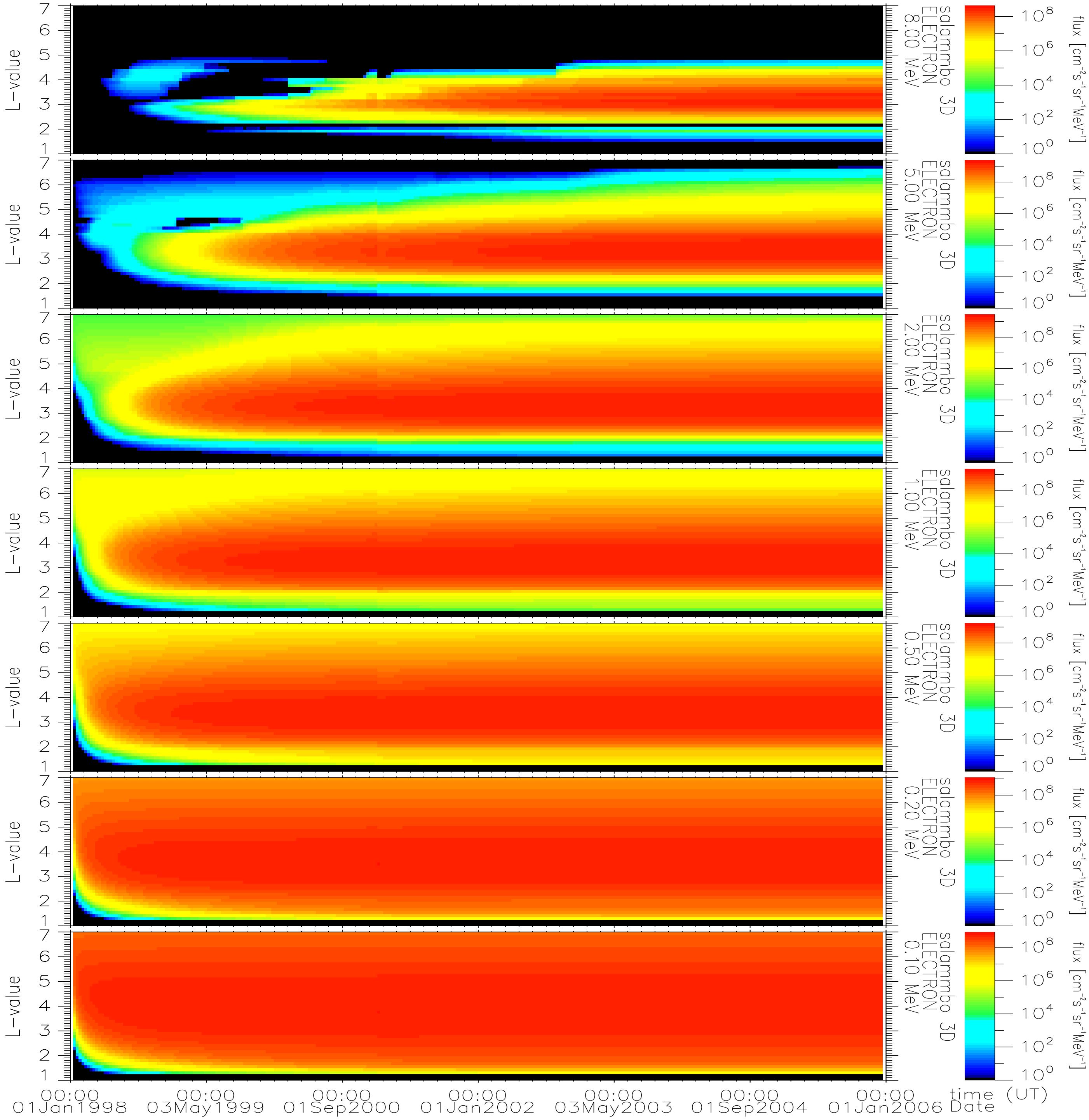
For this paper we use the electron code only (see flowchart in Section C.2)

C.2 The Salammbô Code: The electron radiation belt model



C.3 The Salammbô Code: Stationary state

8 year (30 sec steps) run with AE8 spectrum input at L=7 to obtain a steady state.



D.1a Introducing artificial loss processes: theory

The main loss processes for relativistic electrons are collisions with the atmosphere which leads to a sudden breakdown of trapping. The strength of this process is influenced by pitch angle diffusion towards the loss-cone, either by collisional or frictional mechanisms, or by wave-particle interaction. Increasing the diffusion in these processes will lead to increased particle precipitation and long term flux decrease.

A further mechanism which is important a low L values, near the foot of field lines and for hight energy electrons, is losses due to Synchrotron emission. This has been added to Salammbô, and will not be modified at this stage.

Of all these processes the one which is most feasible in terms of attempting artificial modification is pitch angle diffusion by coherent wave-particle interaction, as this can be achieved by man-made waves.

Friedel [1991] has shown that by designing the correct wave sequence (keeping particles in resonance with the wave along the whole field line) a large effect can be achieved with a low-intensity wave, which reduces the power requirements to the realm of a feasible satellite mission.

D.1b Introducing artificial loss processes: theory

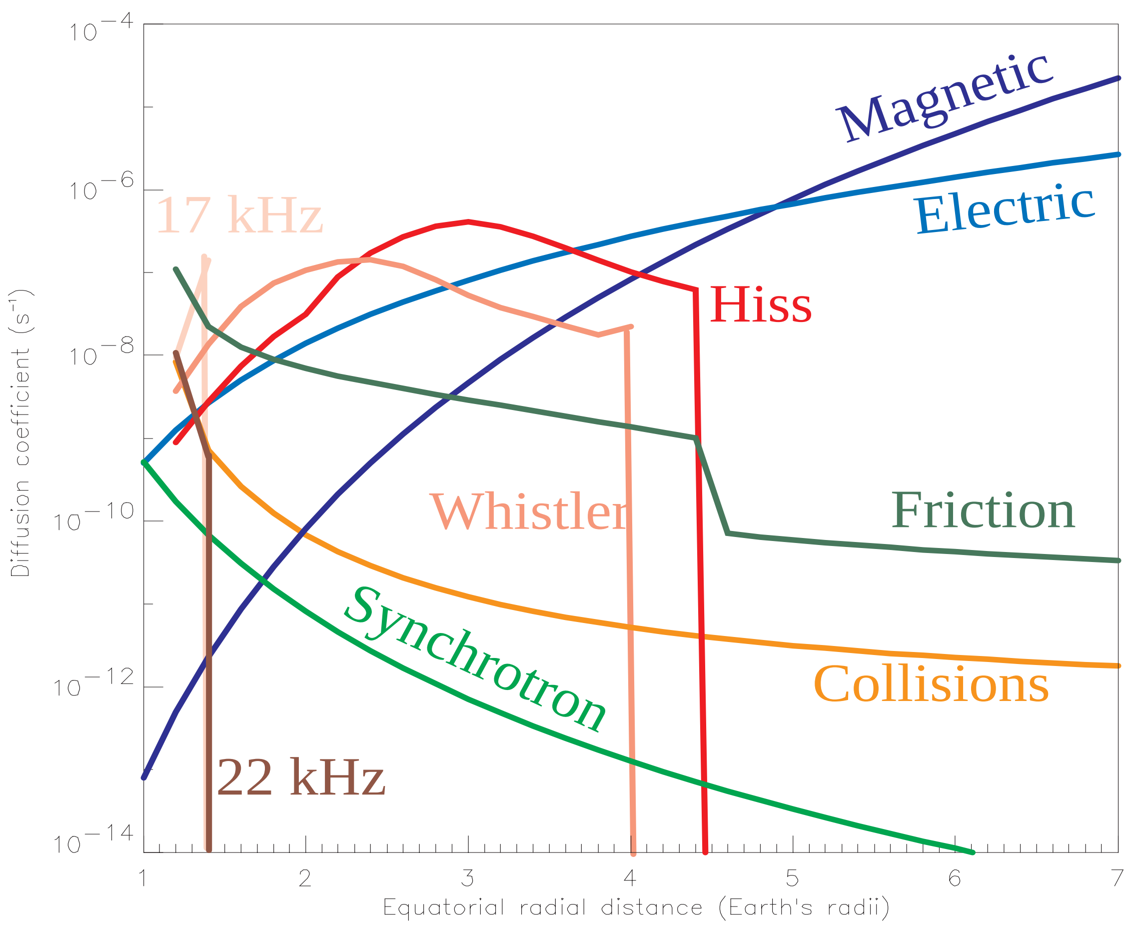
In this model the contribution of wave-particle interaction to the generalized diffusion equation is represented by a set of pitch angle diffusion coefficients (D_{XX}) which are calculated for all the grid points of the simulation:

Radial diffusion

Pitch angle diffusion

Energy degradation

Diffusion coefficients for 400 keV, 85 degree pitch angle electrons



D.1c Introducing artificial loss processes: theory

This models the effect of HISS and other coherent and incoherent VLF waves on the particle distribution is largely responsible for the generation of relativistic electrons near the plasmapause.

This is limited in the model to the plasmapause location at L=4.3 which is the natural cut-off for hiss generation. Relativistic particles are generated by the model here and then diffuse both outward and inward.

As we intend to introduce artificial pitch angle diffusion produced by coherent waves outside of the plasmapause, it is not convenient to modify the hiss pitch angle diffusion coefficients.

The idea here is to affect the source population of relativistic electrons BEFORE they diffuse into the region of the plasmapause. This source is in the keV range which requires lower power for any induced wave-particle interaction.

D.2 Introducing artificial loss processes: model

From a modeling point of view it does not matter which process we adjust in the model to achieve greater pitch angle diffusion towards the loss cone. The exact mechanism used to achieve this in reality is not defined at this point.

We choose here to adjust the pitch angle coefficients for Coulomb collisions as this process most closely mimics the result we wish to achieve artificially. Also, the "natural" Coulomb collision diffusion around L=6 is very low.

The Salammbô Code allows one to modify D_{XX} selectively for a given region in the magnetosphere, a given energy and pitch angle range. Doing this is the same as introducing an artificial loss process. The ΔD_{XX} then needed to achieve the desired effect is then equal to the additional diffusion which needs to be achieved by artificial means.

We do not at this point attempt to specify the actual artificial process needed to modify the pitch angle diffusion in this way, but rather attempt to investigate the parameter space to find the location and extend of the region in the magnetosphere, the energy range and the pitch angle range that needs to be modified to achieve the maximum result with the least amount of modification.

E.1 Long term modeling: Outline

The Energetic Particle Team
at Los Alamos National Laboratory

Using the steady state solution of section C.4 as a start point we run the Salammbô Code with a range of modified pitch angle diffusion coefficients and observe the long-term effect on the relativistic particle population.

In order to introduce realistic modification to the code we use the following rationale:

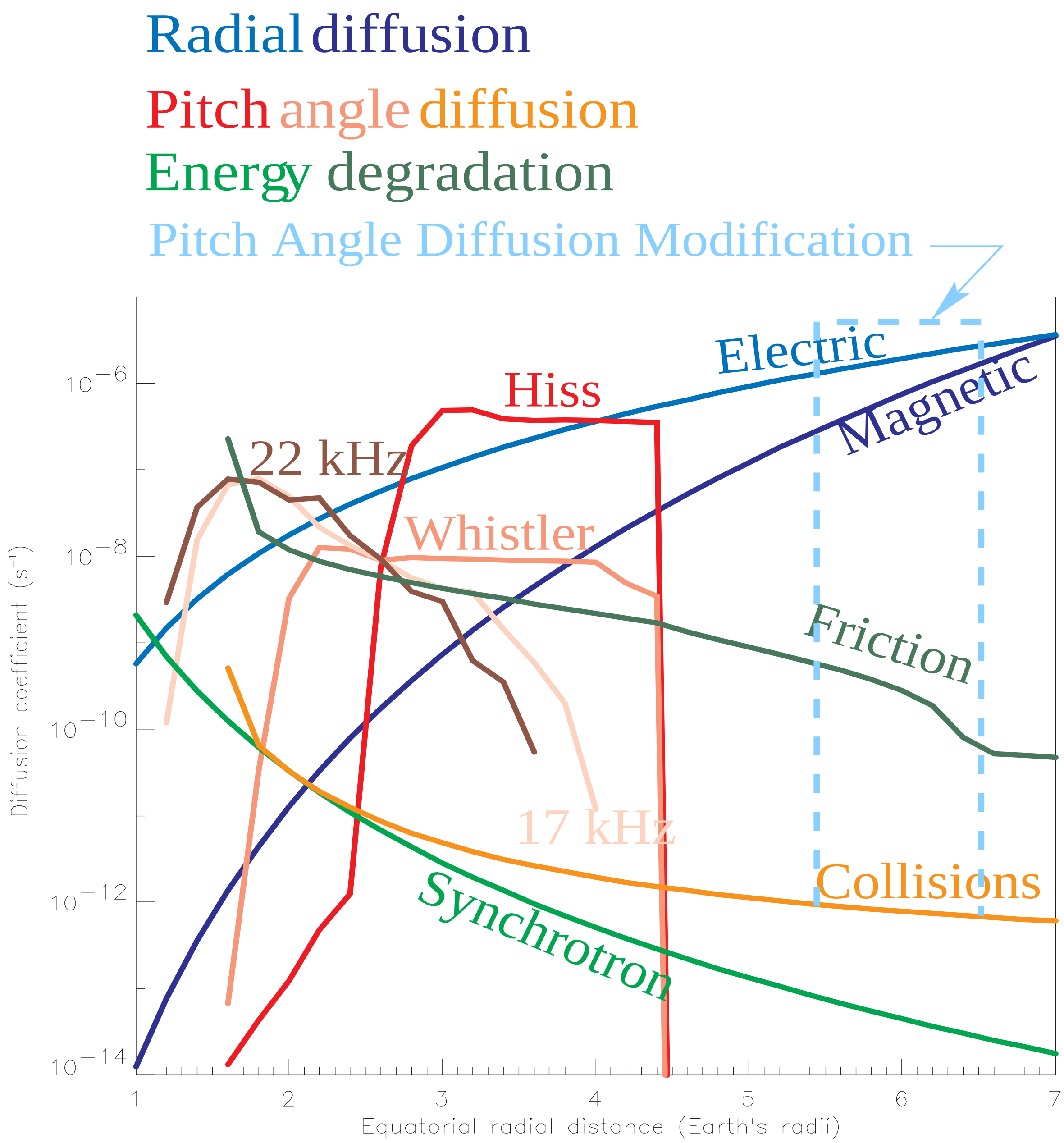
4. Instead of trying to modify the whole distribution function, we limit ourselves to increasing diffusion near the loss cone. Natural diffusion processes, in an attempt to isotropize the distribution, then do the rest of the work!

4. A large amount of relativistic electrons are produced by wave-particle interactions with hiss near the plasmapause [*Beutier and Boscher*, 1995]. The input to this process are electrons around 100 keV which diffuse in from the boundary of the simulation. Thus an effective way of reducing this population is to "catch" $\sim$ 100 keV electrons near geostationary orbit and to reduce their fluxes before they get near the plasmapause. We thus modify pitch angle diffusion above L=5.5 and limit the effect to 100 to 500 keV electrons.

4. The strength and location of the modification needed is a matter of trial and error...

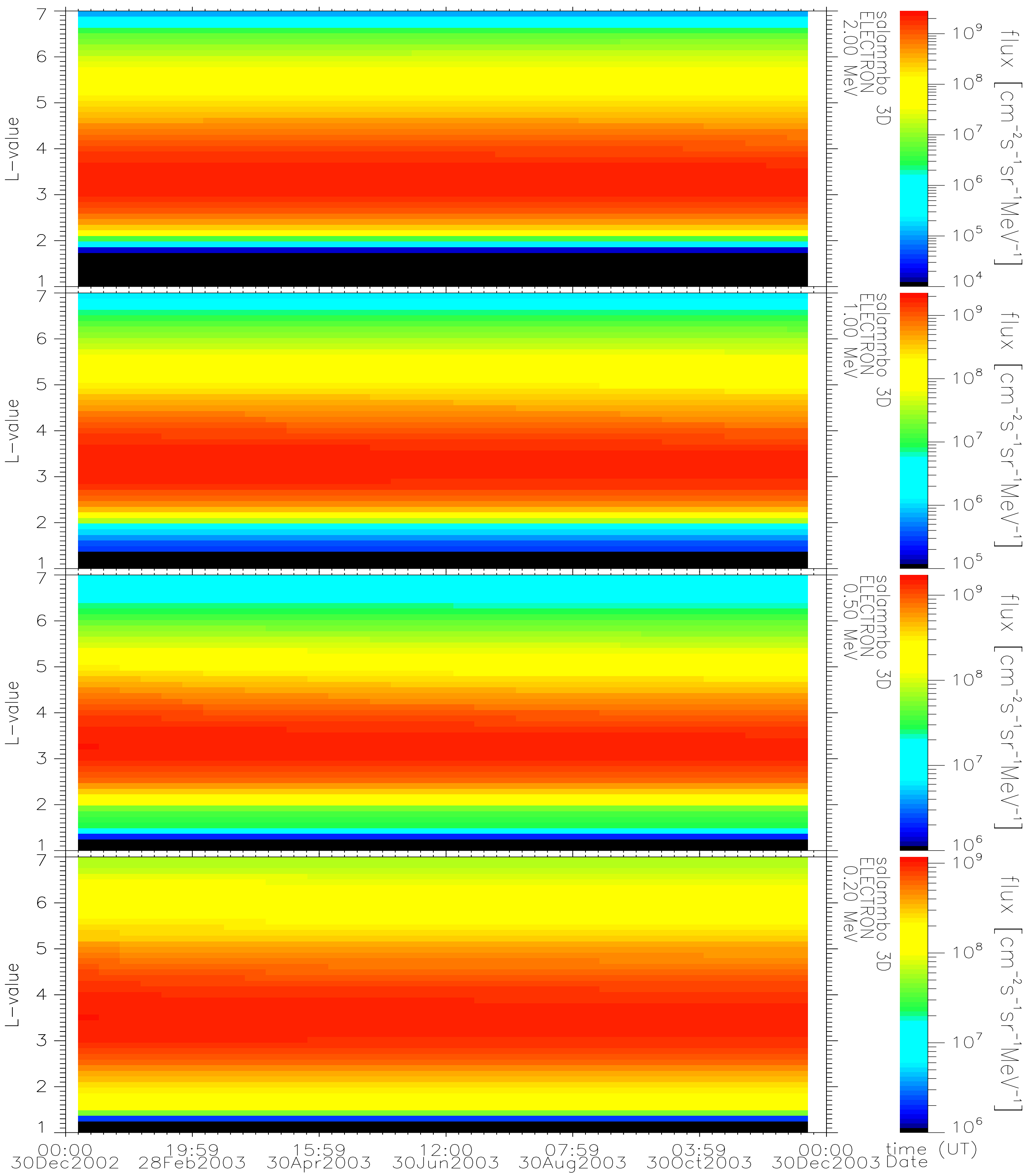
E.2 Long term modeling: Modification of parameters

L–range: 5.5 to 6.5, Energy range: 0.1 to 0.5 MeV
Equatorial pitch angle range: 0^o to 45^o
Duration: 12 months in 30.0 sec steps



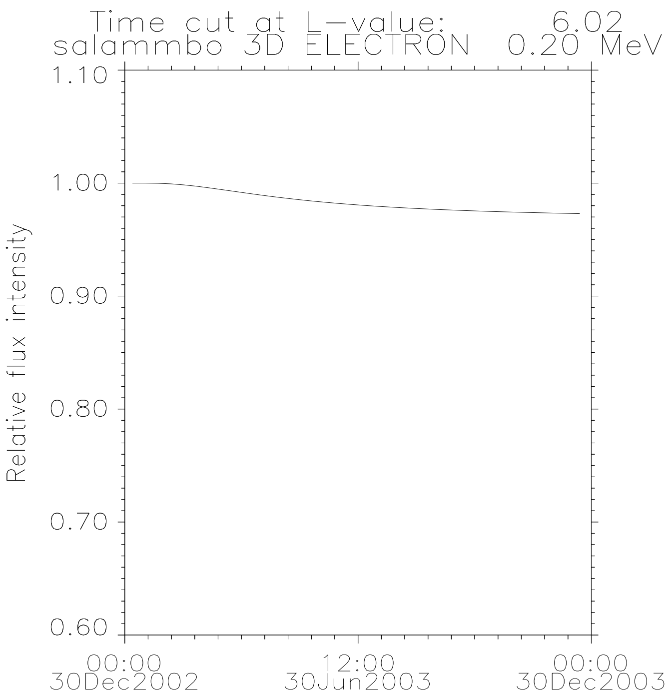
Diffusion coefficients for 400 keV, 30 degree pitch angle electrons

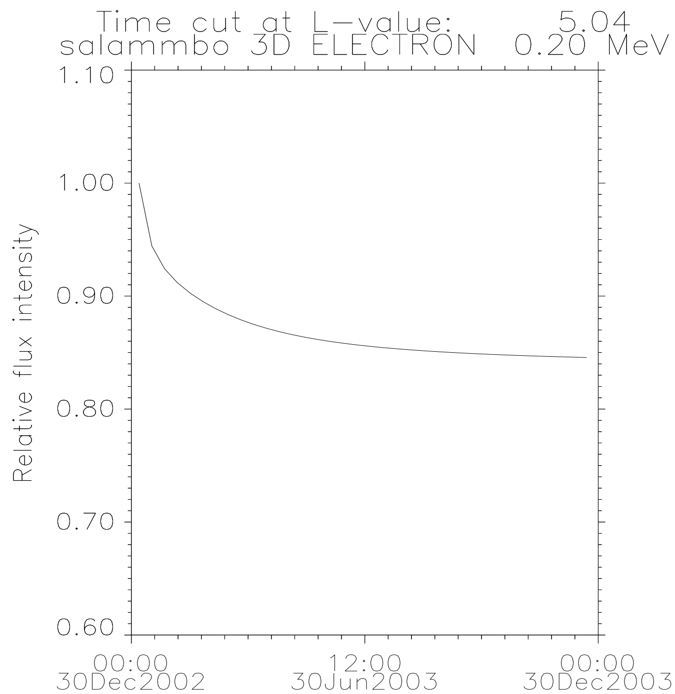
E.3 Long term modeling: Radiation belt modification

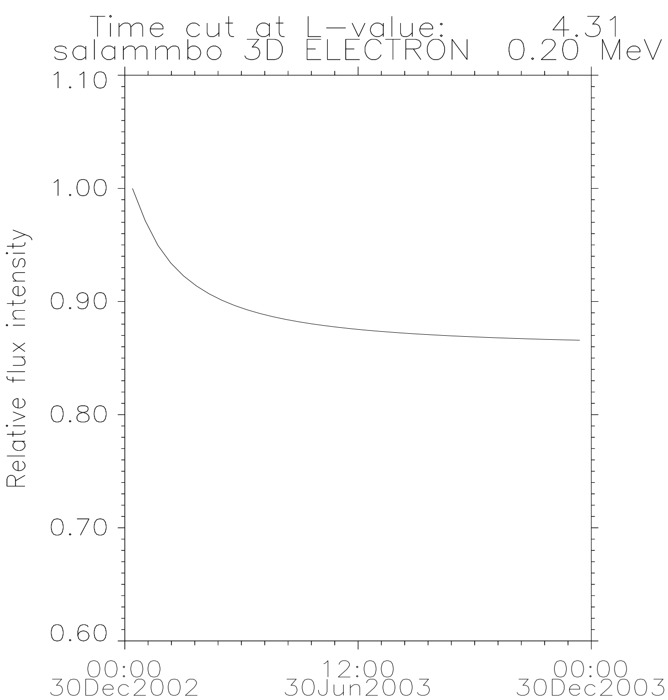


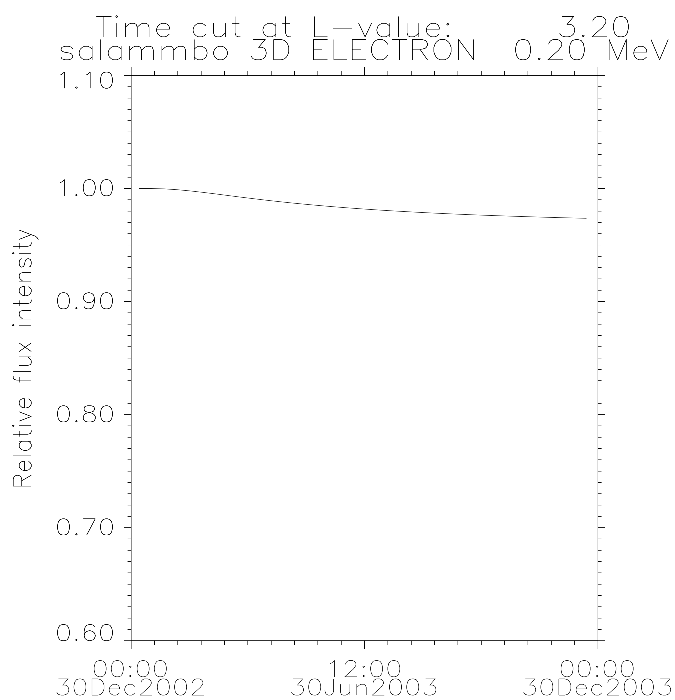
E.3a Long term modeling: Reduction in flux: 0.2 MeV

Data is normalized to flux values at beginning of simulation.



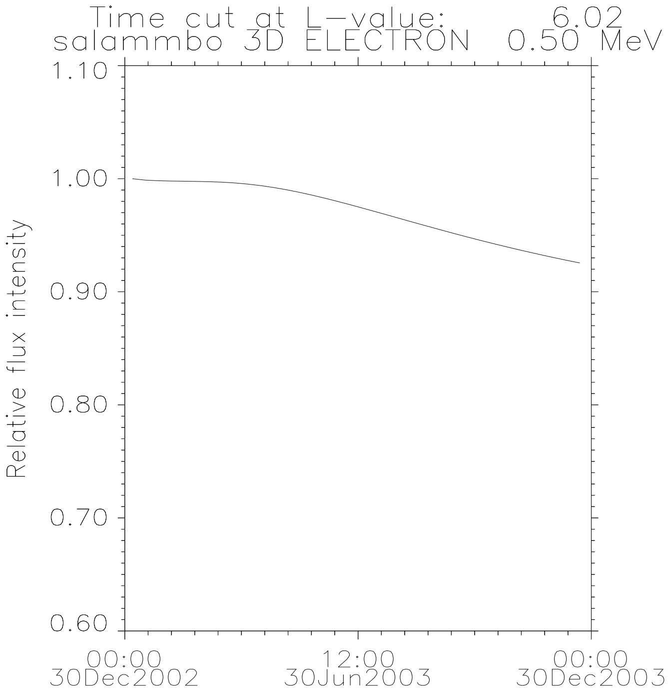


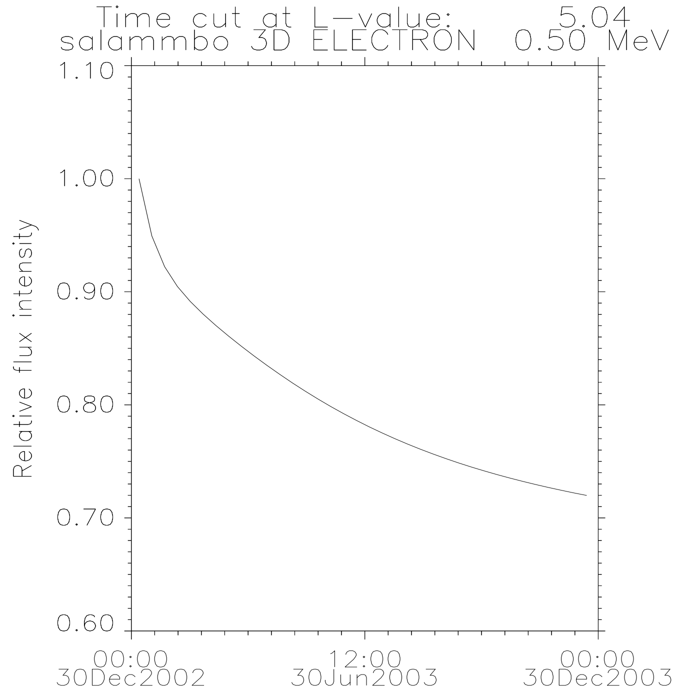


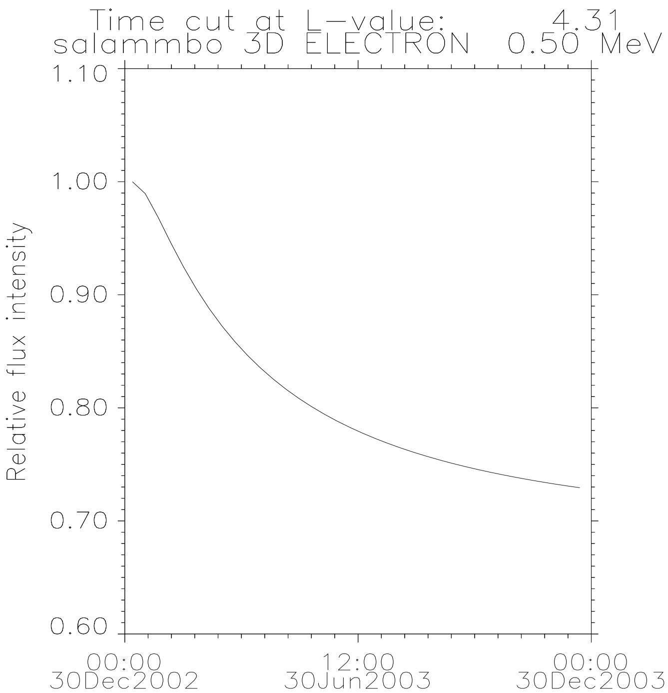


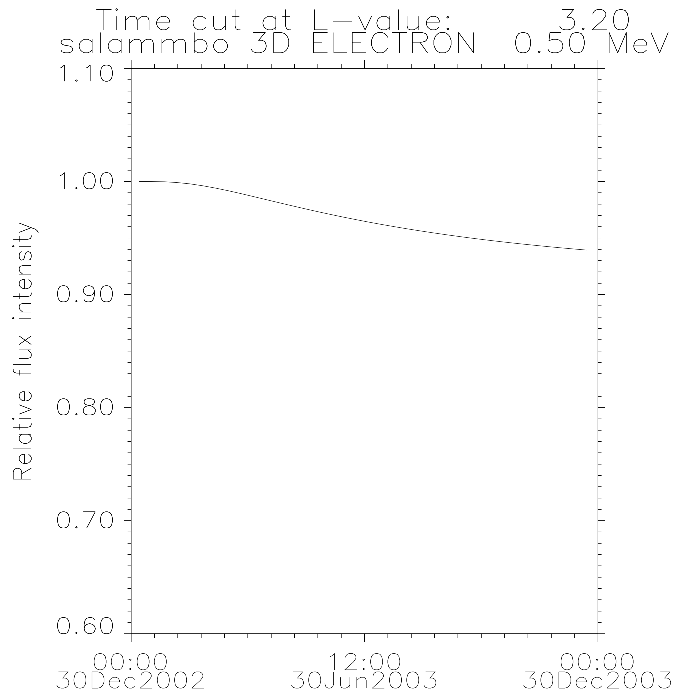
E.3b Long term modeling: Reduction in flux: 0.5 MeV

Data is normalized to flux values at beginning of simulation.



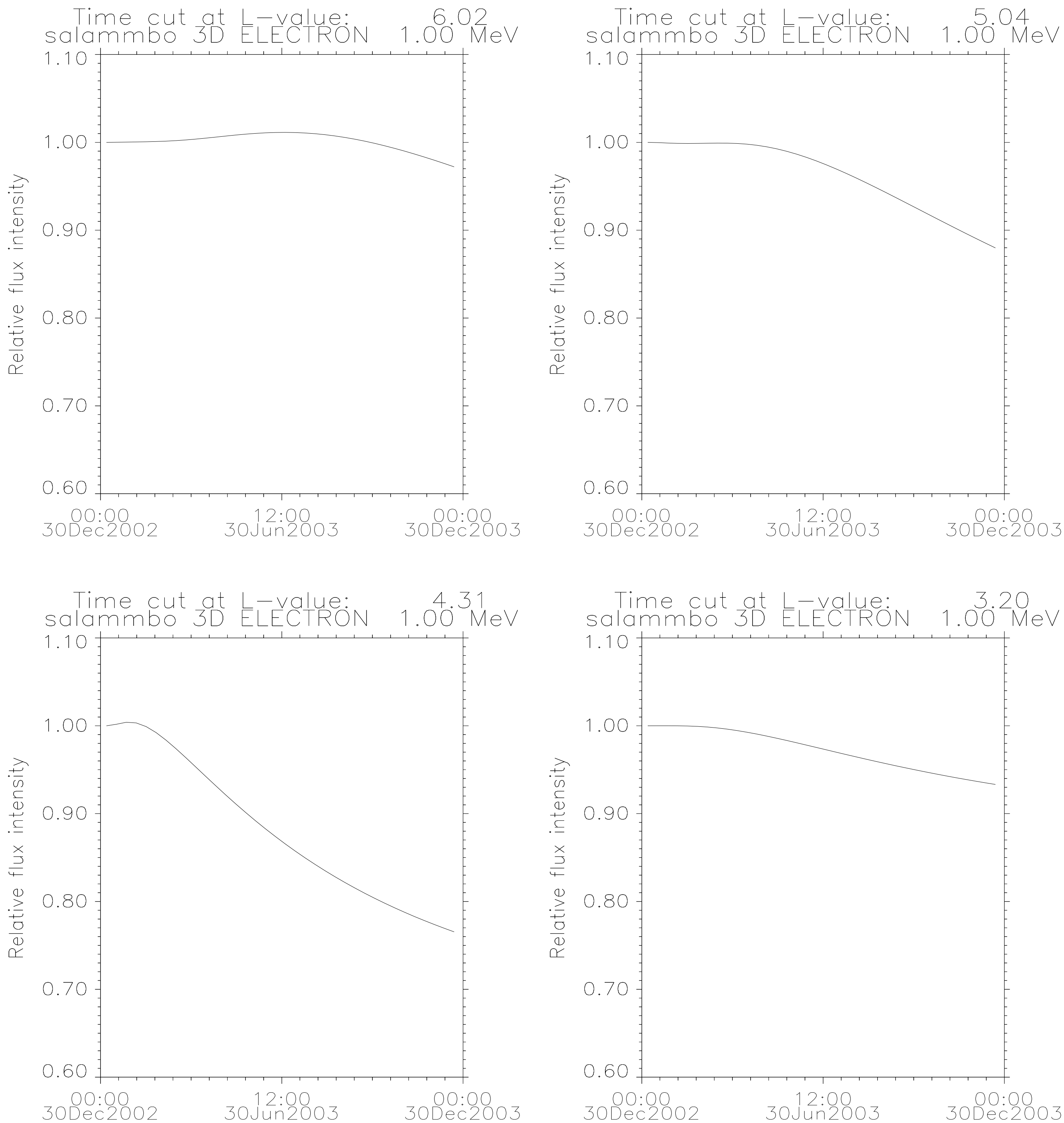






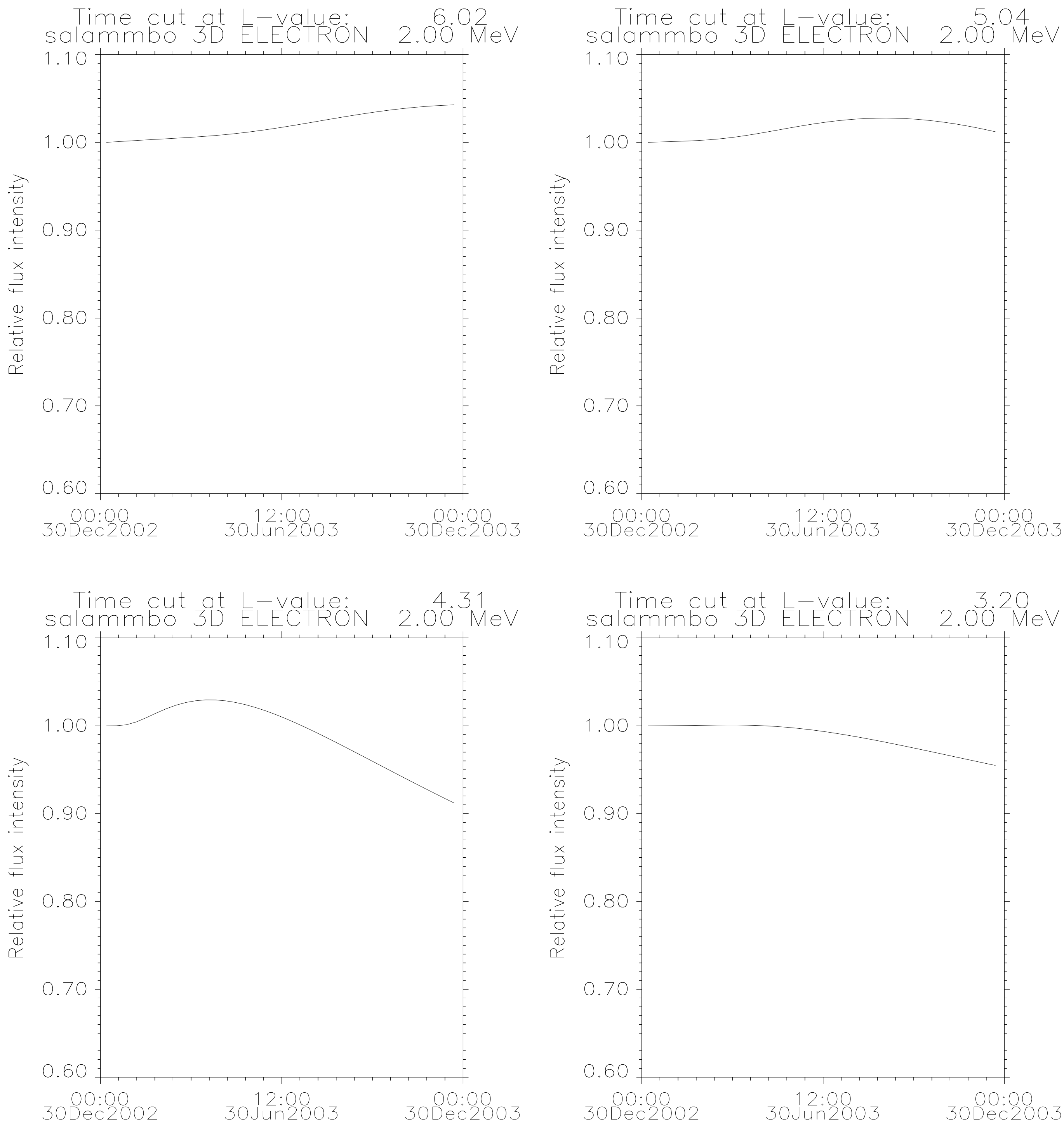
E.3c Long term modeling: Reduction in flux: 1.0 MeV

Data is normalized to flux values at beginning of simulation.



E.3d Long term modeling: Reduction in flux: 2.0 MeV

Data is normalized to flux values at beginning of simulation.



F. Results - Conclusions?

- The Salammbô model has proven to be very well suited to modeling the results of artificial pitch angle diffusion.
- We have shown that a modification of pitch angle diffusion in a limited region of the magnetosphere can have global effects.
- By choosing the correct energy range and position of the modification particle fluxes at higher energy further inside the magnetosphere can be reduced. This is an important result for practical consideration: the lower the energy of the particle, the lower the wave power needed to produce the desired pitch angle diffusion.
- The highest reduction of flux was achieved near the plasmapause, where wave-particle interaction with Hiss provides a natural acceleration mechanism for MeV particles. This shows that we have successfully reduced the seed population near the plasmapause.
- These preliminary results indicate that a more thorough search of the parameter space for the modification position and range is needed.
- The new Salammbô Code is not completely stable yet. High energies do not settle down to a good steady state, and the slot region is not reproduced.

G. References

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